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# DETERMINATION OF HEAVY NUCLEI CHARGES

V. B. Semikoz*

ABSTRACT. The number of δ-electrons formed by $\eta = \frac{Z}{137\beta}$, where Z is the charge, $\beta = \frac{v}{c}$ is the velocity of the nucleus, is calculated.

Good agreement was observed with the Born formula (at $\eta < 0.3$) and with the Rutherford formula (at $\eta > 1.5$), which give the same results in extreme cases ($\eta \ll 1$ and $\eta \gg 1$, respectively).

If the parameter $\eta \sim 1$, then it is necessary to use the exact Mott formula for differential cross sections whose numerical integration is carried out with allowance for kinematic scattering of the nucleus by target electrons.

In this case, the introduced correction to charge $Z_{15}$, determined in the first Born approximation, is very large, especially for the heavy nuclei of the SH group.

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Lately, great interest has been aroused by experiments to detect superheavy nuclei, carried out at the atmosphere boundary. In such experiments the charge, in particular, is determined from formation density of the δ-electrons.

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**Numbers in the margin indicate the pagination in the original foreign text.

The determination of the velocity $\beta = \frac{v}{c}$ and nucleus charge Z can be done using different experimental methods. In particular, in [1], the velocity of the relativistic nucleus was determined from the geomagnetic threshold and the charge — by comparing the blackenings in photoemulsions caused by an unknown nucleus and by iron nuclei (Z = 26).

In the theoretical interpretation of experimental data in [1], the first Born approximation, in which blackening (and also the number of δ-electrons) is proportional to $Z^2$, was used. This appears to be reasonable as applied to light and medium nuclei and even to nuclei of group VH (iron group).

However, for relativistic nuclei with a very large charge, the Coulomb parameter is $\eta = \frac{Z}{137\beta} \sim 1$; it is also necessary to account for the contribution of the subsequent terms of a series in perturbation theory, which was not done in study [1].

In study [2], a calculation was made of the contribution of the second Born approximation, and it was shown that the corresponding correction to the charge being determined significantly exceeds the experimental errors in Fowler's experiments [1].

However, at $\eta \sim 1$ it is also necessary to account for the subsequent contributions of perturbation theories, which can be done by using the exact Mott solution [3] for Coulomb scattering of two particles. /4

Such an evaluation was made by Fowler [4], but the deviation from $Z^2$ — the dependence of blackening (or the number of δ-electrons) on the charge — was determined from the ratio of differential cross sections at some fixed energy of δ-electrons:

$$R(W) = \frac{\sigma_{Mott}(W)}{\sigma_{Ruth}(W)}, \qquad (1)$$

where $\sigma_{Ruth}(W)$ is Rutherford cross section for scattering which coincides with the cross section $\sigma_{15}(W)$ of the first Born approximation. If W = 50 keV, corresponding to a distance $\sim$ 10 μm from the path of the particles, then the ratio R(w) of an order $\sim$ 1 was used by the authors [4] as an argument justifying the application of the Born formula and the accuracy of the earlier evaluations [1].

Indeed, the number of δ-electrons is proportional not only simply to the differential Mott cross section, but also to the same cross section integrated over the range extending from $W_{min}$ (50 keV in Fowler's experiments) to some $W_{max}$. Therefore, the deviation from the $Z^2$-dependence will be determined by the ratio of integrals of the cross sections in Formula (1), calculated in the range determined by the kinematic scattering of the nucleus by target electrons (from $W_{min}$ to $W_{max}$) and dependent on the experimental conditions [5].

The introduced correction: /5

$$\Delta = \frac{N_\delta(\text{Mott}) - N_\delta(15)}{N_\delta(15)}, \qquad (2)$$

where $N_\delta$ (I Б) is the number of δ-electrons calculated in the first Born approximation, reaches, for example, 16% for the uranium nucleus (Z = 92) at the velocity β = 0.8.

In this case, the charge determined from formula

$$Z \cong Z_{15}\left(1 - \frac{\Delta}{2}\right), \qquad (3)$$

is smaller by $|\Delta Z|$ = 7 units than the charge $Z_{15}$ determined by assuming a $Z^2$-dependence of the number of δ-electrons on the charge, which is in agreement with the evaluations given in our study [2].

Let us examine the formation of δ-electrons during the passage through the emulsion of the nucleus which has arbitrary values Z and β.

The number of δ-electrons formed along 1 cm of the track is

$$N_\delta(\text{Mott}) = 2\pi N \int_{\cos\theta_{max}}^{\cos\theta_{min}} \frac{d\sigma_{mott}}{d\cos\theta} d\cos\theta , \qquad (4)$$

where N is the number of electrons in 1 $cm^3$ of emulsion.

$$\cos\theta_{min} = 1 - \frac{W_{min}}{m} \cdot \frac{1-\beta^2}{\beta^2} ,$$

$$\cos\theta_{max} = 1 - \frac{W_{max}}{m} \frac{1-\beta^2}{\beta^2} . \qquad (5)$$

θ is the scattering angle in the system at rest of the incoming nucleus /6
or in the c.i.s. of the nucleus and the δ-electron (nuclear recoil can be ignored).

The ratio (1), the numerator of which is the integrand from Formula (4), is tabulated, for example, in the studies of Doggett [6] and Sherman [7] ($6 \leq Z \leq 92$; $0,2 \leq \beta \leq 0,9988$).

We made calculations on a BESM-4 computer by numerical integration of Formula (4) with the interpolation of numerical data from [6] and [7].

The values $W_{min}$ and $W_{max}$ were taken as a function of the velocity of the nucleus β.

The range of δ-electrons with energy $W_{min}$ is equal to the minimum distance from the "core" of the path of the heavy particle $R_{min}$, where the blackening caused by the particle begins to be measured photometrically.

For $\beta > 0.8$ we assume $W_{min}$ 45 keV ($R_{min} \sim 9$ μm). The value $W_{max}$ is selected so that δ-electrons stop in the emulsion and their ionization losses are sufficiently large to form grains ready for development.

The results are shown in the figure. The ordinate axis shows the value of Δ [Formula (2) which determines the deviation from the $Z^2$-dependence of blackening as a function of the charge], and the abscissa axis gives the velocity of the nucleus β.

The figure shows that in extreme cases when

a) $\beta << 1$, ($\eta >> 1$),

b) $\beta \sim 1$, ($\eta << 1$ at small Z),

the correction is $\Delta \to 0$. This means that the number of δ-electrons must be determined from the classical Rutherford formula in case (a) and in agreement with the Rutherford formula, the Born formula in case (b). /7

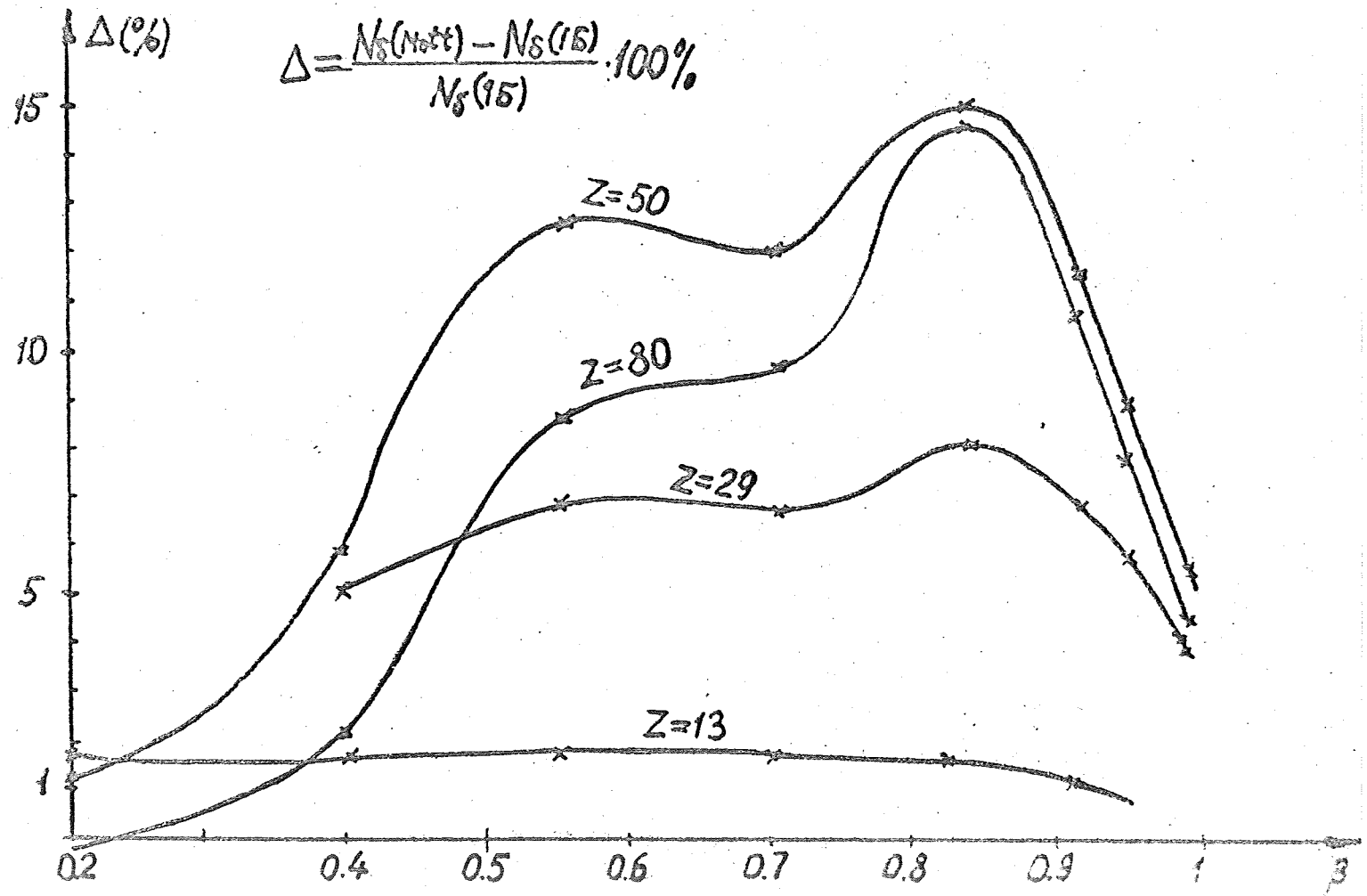
In practice, at $\eta > 1.5$ and $\eta < 0.3$, the correction $|\Delta Z| < 1$ [see Formula (3) and the figure].

It is of interest to note that, even for the heaviest nuclei, for which sometimes $\eta << 1$ does not hold, if the velocity $\beta \to 1$, then the correction is $\Delta \to 0$ (i.e., cross section $\sigma_{\text{мот}} \to \sigma_{\text{рез}}$).

Thus, $|\Delta Z| \to 0$ at $\beta \to 1$, but how can we measure such velocities?

If the relativistic nucleus is recorded by the agreement shown by two Cherenkov counters (one "measures" velocity, the other "measures" charge) then the calculations can be confined to the first Born approximation, even in the case of very heavy nuclei.

This follows directly from the result given by Tidman [8] who calculated the contribution made by the simultaneous emission by the nucleus of two γ-quanta in the counter emitter medium.


Δ(%)
$\Delta = \frac{N_S(Nott) - N_S(15)}{N_S(15)} \cdot 100\%$
15
10
5
1
Z=50
Z=80
Z=29
Z=13
0.2
0.4
0.5
0.6
0.7
0.8
0.9
1
3

In the determination of charges of slow, heavy ions [9] from their energy losses during ionization, an error may arise due to the divergence of theoretical and experimental curves in the region $\eta_{eff} \sim 1$ (see Figure 7 in [9]).

The divergence may be eliminated if the theoretical calculations are carried out from the exact (with respect to parameter $\eta$) Bloch formula [10], in which the following substitution should be made: $\eta \rightarrow \eta_{eff.} = \frac{Z_{eff.}}{137\beta}$ where $Z_{eff.} = Z^{1/3} f(\beta)$ and $f(\beta) \rightarrow 0$ at $\beta \rightarrow 0$ (see [9].

Thus, if in future experiments a question arises concerning selection of the procedure to determine heavy nuclei charges, then from a theoretical point /8 of view, to obtain the highest precision it is most expedient: 1) for relativistic nuclei, to use Cherenkov counters; 2) for nonrelativistic nuclei, to use the emulsion method or the method of ionization losses, and then to introduce the above corrections, which are especially important in the region of Coulomb parameter values $\frac{Z}{137\beta} \sim 1$.

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